# Biophilic Atrium Design: An Analysis of Photosynthetically Active Radiation for Indoor Plant Systems

## Comparison between Two Climates

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*ABSTRACT: Biophilic design aims to bring natural elements into the built environment. In urban buildings, an atrium can be adopted not only as an important passive solution to achieve natural light and ventilation, but also to provide significant biophilic opportunities by nurturing plant growth on floors and façades. Access to Photosynthetically Active Radiation (PAR) is critical for sustaining plant growth in and around the atrium well. Therefore, it is important to investigate the availability of PAR at the early stage of an atrium building design. Using advanced ray-tracing simulations, this study presents the analysis of PAR availability at various positions in atrium buildings, considering shapes, geometries, and climates (Beijing and London). Key findings from the study are: 1) Different from daylight metrics for human vision, the PAR metric Photosynthetic Photon Flux Density (PPFD) could be more useful in terms of planning planting systems in atria. 2) The impact of atrium shape and geometry on PAR availability is significantly linked to position in the atrium, while the effect of atrium geometry will also depend on the shape. 3) It seems that climate conditions might not substantially influence PAR frequency variations based on this metric for plants.*
*KEYWORDS: Photosynthetically Active Radiation, Indoor plants, Biophilic design, Atrium building, Simulation*

### 1. INTRODUCTION

Biophilic design [1], an emerging design concept in the built environment, is increasingly applied to improve occupants' connectivity to the natural environment through direct nature, indirect nature, space and place conditions, and climate. The atrium has been generally adopted in traditional and contemporary architecture as an efficient passive solution to achieve daylighting and natural ventilation, and thus human visual and thermal comfort [2, 3, 4]. An atrium can also produce creative interplays of sky and sun, spaciousness, plants, and water in a deep plan, and to simulate the qualities of natural settings in an indoor space [5, 6]. Thus, in urban buildings, the atrium has been well recognized as one important and practical biophilic design solution.

Studies of atrium daylighting generally target three aspects - occupants, plants, and energy [2, 7]. The atrium floor and façades can be used as possible positions to establish plants of various types and sizes [6, 8]. Plants have been shown to be an effective biophilic solution to achieve a direct contact with nature for building occupants [4]. To maintain plant growth within the atrium is one of key objectives for sufficient daylight level needs in atria [2]. Plants require plentiful amounts of natural light to support fundamental photosynthesis processes, and maintain normal growth [9, 10]. It is recommended that typical needs of common plants lie in the range of 700 to ~1000 lx for twelve hours a day and that top lighting is more desirable as a direction-giver [2]. Therefore, daylighting in an atrium has been regarded as one of the most difficult environmental factors to predict and control on the basis of plant maintenance for the interior [2]. In many atrium buildings, supplementary electric lighting will have to be used to sustain the planting [9, 10]. However, the use of electric lighting would not just increase energy consumption, but also bring in undesirable negative effects on a biophilic space, where man-made environmental factors and relevant control measures should be minimized or even avoided [5].

For the planting in a controllable facility (e.g. chamber, greenhouse), the light levels required by plants can be measured by illuminance (unit: lux) or Photosynthetically Active Radiation (PAR, unit: $W/m^2$ or $\mu moles/m^2/s$) [10, 11]. The concept of illuminance was developed based on the human visual system [9], and it was also applied by horticultural scientists to indirectly indicate how much light is required by the plants [9]. Photosynthetically Active Radiation (PAR), the spectral range (wavelength) of solar radiation (400 to 700 nm) that photosynthetic organisms use in the process of photosynthesis, is a direct metric of energy critically required for sustaining plant and vegetable growth [10]. PAR varies seasonally and changes based on time of day and site latitude [10].

Investigating the availability of PAR is necessary when planning an indoor planting scheme and the relevant facilities for growing the plants.

Using advanced ray-tracing simulation and various weather data, this study presents the first analysis of PAR availability and distributions in atrium buildings, taking into consideration shape, geometries, and locations. The results could be developed into design guidelines for the establishment of a biophilic atrium with a high potential to bring indoor a 'green nature' for building occupants.

## 2. METHODOLOGY

### 2.1 Locations and climates

Two atrium locations with different climates were selected in this study - Beijing in China (39.9° N, 116.4° E) and London in UK (51.5° N, 0.128° W). Beijing has a continental climate with a cold winter and a hot and humidity summer, whilst a typical temperate oceanic climate is found in London. Total annual sunshine hours of Beijing and London are 2478 and 1481, respectively. Beijing has 67% more sun shining hours than London, indicating a much higher level of daylight availability.

### 2.2 Atrium models

At each location, two typical atrium models were digitally modelled with square and round floor plans (Figure 1). These models had a flat double-glazed roof with a visual transmittance 0.64, and their wall and floor have reflectance of 0.4 and 0.2, respectively.

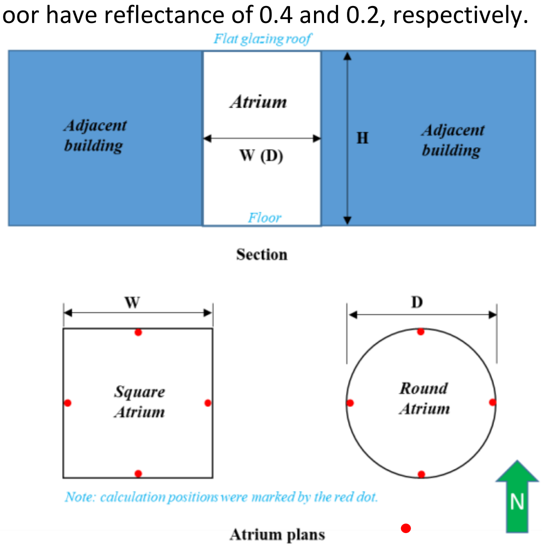


*Figure 1: Section and plans of two atrium models.*

Based on the configurations in Figure 1, six atrium models were studied in terms of shape and dimensions (Table 1). For a square atrium, the Well Index (WI) can be expressed by the equation:

$$WI = H/W \quad (1)$$

where H and W are the height and width of the atrium well respectively. Three types of square atrium were studied: shallow atrium (WI = 1), normal atrium (WI = 1.5), and tall/narrow atrium (WI = 2). Similarly, the round atrium was categorized by the same three heights as the square atrium. For each height, the volume of the round atrium equalled that of the square one.

*Table 1: Atrium types and geometries.*

| Shape | Name | W (m) | D (m) | H (m) | Well Index |
|---|---|---|---|---|---|
| Square | S-WI1 | 18 | | 18 | 1.0 |
| | S-WI1.5 | 18 | | 27 | 1.5 |
| | S-WI2 | 18 | | 36 | 2.0 |
| Round | R-WI1 | | 20.32 | 18 | |
| | R-WI1.5 | | 20.32 | 27 | |
| | R-WI2 | | 20.32 | 36 | |

### 2.3 PAR simulation and metrics

Generally, PAR is quantified in terms of Photosynthetic Photon Flux Density (PPFD, μmoles/m2/s) [10, 11]. One indoor gardening guide book [11] provides PPFD ranges for sustaining the growth of indoor plants, such as (i) lower level (9.5-47.5 μmoles/$m^2$/s); for example, Ficus Lyrate, Schefflera, Asparagus Fern; (ii) higher level (47.5-190 μmoles/$m^2$/s); for example, Bromeliad, European fan palm, Mock Orange Bush. A very low PPFD (<9.5 μmoles/$m^2$/s) and a very high PPFD (>190 μmoles/$m^2$/s) will not be able to sustain a healthy growth of indoor plants. Thus, a PAR metric was applied based in this study on these four PPFD ranges.

The PAR calculations in the atrium models were achieved using the following steps: 1) The daylight illuminance (lux) at specific positions was simulated using the lighting software DAYSIM/RADIANCE and the weather data of the two locations; 2) The illuminance (visual part of solar irradiance spectrum) was converted to PPFD (μmoles/$m^2$/s) using the algorithm given in [10]: PPFD = 0.0185 × Illuminance. The daily analysis of PPFD was only considered within a daytime period of 9:00 - 16:00 [11]. The ambient settings for the RADIANCE simulations [12] were: Ambient Divisions 2048; Ambient Bounce 9; Ambient Super-Samples 1024; Ambient Resolution 128 and Ambient Accuracy 0.1. These atrium settings had been validated in a previous study by the authors [3].

Given the aim to place indoor plants in an atrium, this study investigated PAR availability at the centre atrium floor and three different façade heights, including low position (1/4H), middle position (1/2H), and high position (3/4H). Those calculation positions at atrium facades can be found in Figure 1 (red dots).

In this study, the PAR availability was assessed using the annual frequency in terms of the four PPFD ranges mentioned above. PAR levels at the façade were expressed by the averaged value of four positions at the same vertical position. The centre of the atrium floor PAR levels represented this area.

## 3. RESULTS

### 3.1 PAR performances on the atrium floor

Figures 2 and 3 show annual PPFD frequencies (four ranges) at the centre of the atrium floor for the six atrium models in Beijing and London, respectively.

In Beijing (Figure 2), square and round atrium models have similar varying trends of PPFD frequencies. Increasing WI or height will significantly increase the frequency of PPFD (<9.5) at the centre floor, while the frequency of PPFD (47.5-190) decreases. The tall atrium models (WI = 2.0) had no PPFD values falling in the range (47.5-190). Interestingly, the varying WI just slightly impacts on frequencies of PPFD (9.5-47.5). In general, all models can achieve the combined 'green' PPFD frequencies (9.5-190) > 50%, while high PPFD (>190) frequencies can be found in WI = 1.0 & 1.5 (< 5%). Thus, it seems that the PAR available at the atrium floor could be possible to sustain the normal growth of plants over half the working year.

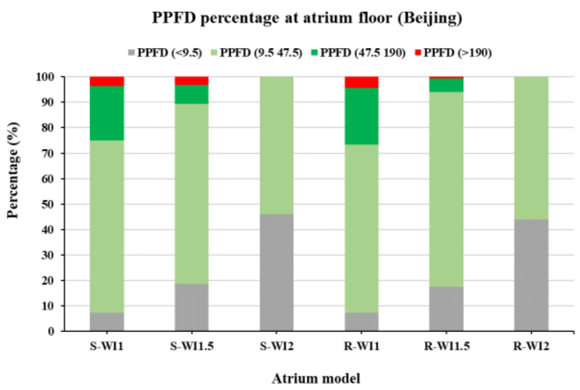


*Figure 2: Frequencies of PPFD range at centre floor in various atria (Beijing).*

For London (Figure 3), similarly, there are no big differences of PPFD frequencies found in square and round atrium models. The frequencies of PPFD (<9.5) tend to be larger with the increasing WI or height. As shown in Figure 3, There are no PPFD values falling in the range of (>190) in London, while only shallow atrium models (WI = 1.0) see the frequency of PPFD (47.5-190) of around 20%.

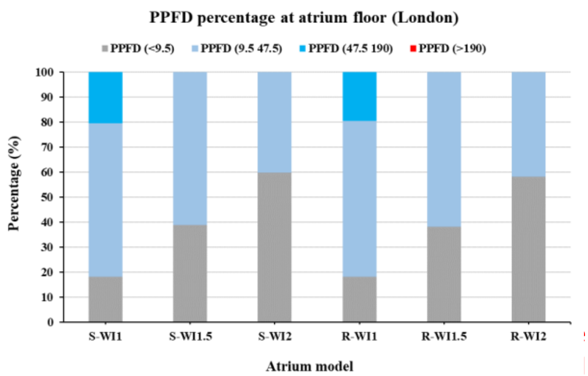


*Figure 3: Frequencies of PPFD ranges at centre floor in various atria (London).*

The shallow atrium models have very similar frequencies of PPFD (9.5-47.5) for normal atrium models (WI = 1.5). However, tall atrium models (WI = 2.0) achieve relatively lower PPFD (9.5-47.5) frequencies. Compared with Beijing (Fig. 2), London sees lower frequencies of PPFD (9.5-190), especially for tall atrium. However, all models achieve the frequency > 40%, and it possible to grow plants at the atrium floor in London for ~40% of the working year.

### 3.2 PAR performances at low levels of atrium façade

Figs. 4 and 5 present annual PPFD frequencies (four ranges) at the low levels of the atrium façade in six atrium models for Beijing and London, respectively. In Beijing (Fig. 4) there are big differences of PPFD variations between square and round models. For the square model, an increasing WI reduces frequencies of PPFD (9.5-47.5) and PPFD (47.5-190), while increasing the frequency of PPFD (< 9.5). The tall atrium model (WI = 2) has the frequency of PPFD (9.5 190) < 35%, indicating a low possibility to place plants at this position. However, for the round model, frequencies of PPFD (< 9.5) are less than 2%, while relatively higher frequencies of PPFD (>190) can be found at all heights (all values > 20%). Frequencies of PPFD (9.5-47.5) are generally higher than 65%. For each model, frequencies of PPFD (47.5-190) are much higher than frequencies of PPFD (9.5-47.5). This suggests that there is a high possibility to place plants at low façade levels in round models.

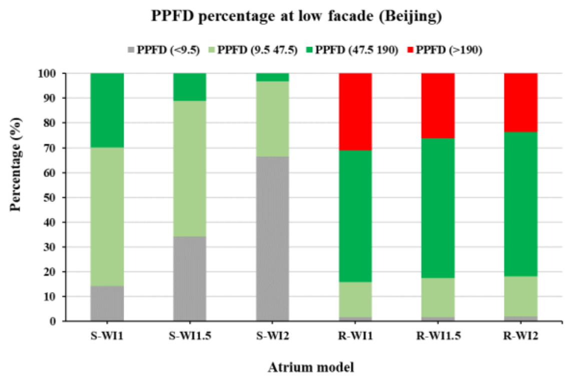


*Figure 4: Frequencies of PPFD ranges at low levels of the atrium facade in various atria (Beijing).*

For London (Fig. 5) similar variations of PPFD frequency in two types of atrium are seen. In general, the varying PPFD frequencies of square models are significantly different from round models. Compared with round models, square models see lower PPFD (9.5-190) frequencies and much higher PPFD (<9.5) frequencies. Round models have relatively higher PPFD (> 190) frequencies (all values > 10%), while these values cannot be found in any square model. Increasing the WI increased the PPFD (<9.5) frequency in square models, while significantly decreasing frequencies of PPFD (9.5-47.5) and PPFD (47.5-190). In addition, heights of round models do not have a significant impact on frequencies of PPFD (< 9.5), PPFD (9.5-47.5), and PPFD (47.5-190). Frequencies of PPFD (47.5-190) are higher than those of PPFD (9.5-47.5) in round models. Moreover, frequencies of PPFD (9.5-190) were over 70% in all round models. However, square models can see these values > 50% only when WI = 1. It could be found that for a location dominated by overcast skies the round atrium can still provide higher opportunities for plants applied at low atrium façade levels.

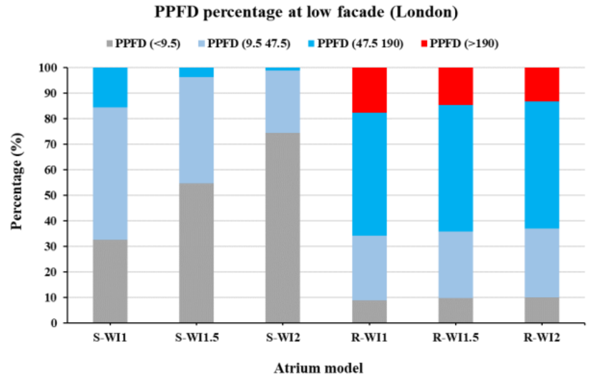


*Figure 5: Frequencies of PPFD ranges at low levels of the atrium façade in various atria (London).*

### 3.3 PAR performances at middle level atrium facade

The distributions of annual PPFD frequencies (four ranges) at the middle atrium façade level in the six atrium models are presented in Figs. 6 & 7 for Beijing and London respectively. In Beijing (Figure 6), the middle façades levels generally have high frequencies of PPFD (9.5-190) in both square and round models. The frequencies achieved in square and round models are >70% and > 65%, respectively. For square models, interestingly, increasing WI could increase frequencies of PPFD (9.5-47.5), while decreasing frequencies of PPFD (47.5-190). Frequencies of PPFD (9.5-47.5) are generally higher than those of PPFD (47.5-190). No PPFD (>190) values can be found at middle façade level of the square model.

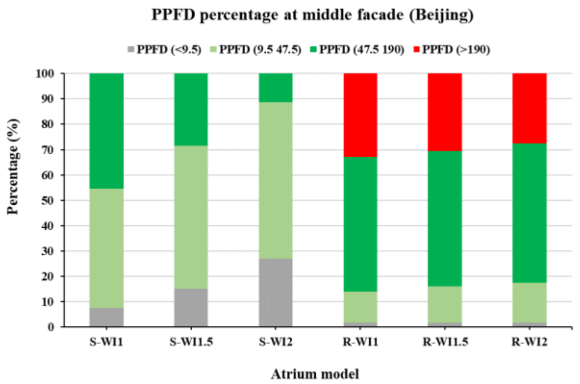


*Figure 6: Frequencies of PPFD ranges at middle atrium facade in various atria (Beijing).*

For round models, the varying height cannot significantly change frequencies of PPFD (9.5-47.5) and PPFD (47.5-190). Frequencies of PPFD (>190) were above 27% at all heights, while frequencies of PPFD (< 9.5) were less than 2%. Different from square models, round models can see higher frequencies of PPFD (47.5-190) than those of PPFD (9.5-47.5). It seems that the choice of suitable types of plants would be linked with the type of atrium plan.

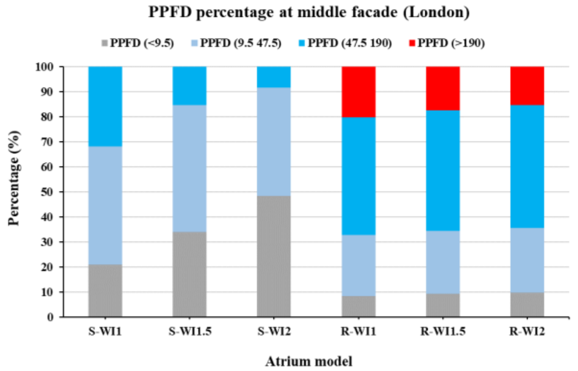


*Figure 7: Frequencies of PPFD ranges at middle atrium facade in various atria (London).*

Similar trends of PPFD frequency variations can be found for London (Fig. 7). At the middle level, both square and round models have high frequencies of PPFD (9.5-190). All square models have the values above 50%, while these values for round models are over 70%. An increasing WI increased frequency of PPFD (< 9.5), while decreasing frequencies of PPFD (47.5-190). However, no clear impact of WI can be found for the frequency of PPFD (9.5-47.5). Square models see higher frequencies of PPFD (9.5-47.5) than PPFD (47.5-190). In round models, similarly, no big impact of atrium height can be found on frequencies of the four PPFD ranges. Frequencies of PPFD (> 190) in all models were larger than 15%, while PPFD (< 9.5) frequencies were lower than 10%. Compared with the frequency of PPFD (9.5-47.5), a higher frequency of PPFD (47.5-190) was achieved in each round model. Thus, the atrium plan type can affect the plant types placed at middle façade levels.

### 3.4 PAR performances at high atrium façade levels

Figs. 8 and 9 show distributions of annual PPFD frequencies (four ranges) at the high atrium façade level for the six atrium models in Beijing and London, respectively. For Beijing (Fig. 8), it can be seen for square models that frequencies of PPFD (9.5-190) are over 90%. Compared with square models, round models see lower frequencies of PPFD (9.5-190). However, this value for each round model is still higher than 60%. In square models, shallow and normal atria (WI = 1.0 and 1.5) have higher PPFD (47.5-190) frequencies than PPFD (9.5-47.5) frequencies, while a tall atrium (WI = 2.0) sees similar frequencies between the two PPFD ranges (around 45%). For round models, there are higher frequencies of PPFD (>190) for three heights, such as 36% (R-

WI1), 35% (R-WI1.5), and 33% (R-WI2.0). Similar to results in Sections 3.2 & 3.3, no big impact of atrium height can be found on frequencies of PPFD (9.5-47.5) and PPFD (47.5-190) in round models. The PPFD (47.5-190) achieved much higher frequencies than the PPFD (9.5-47.5). It seems that plants requiring a higher PPFD (> 47.5) would be suitable for this façade position. In addition, the square plan for an atrium could be a proper solution to grow plants at this position.

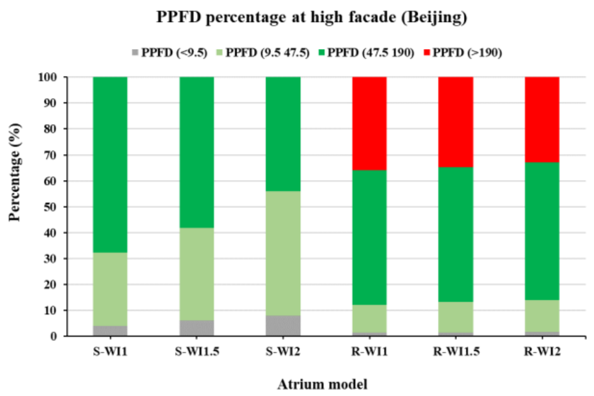


*Figure 8: Frequencies of PPFD ranges at high atrium facade levels in various atria (Beijing).*

In London (Fig. 9), similar varying trends of PPFD frequencies can be found. Both square and round models have high PPFD (9.5-190) frequencies (over 65%). Without any PPFD (>190) values, square models receive higher PPFD (9.5-190) frequencies than round models, while PPFD (> 190) frequencies in round models fall in a higher range of 20% ~ 24%. For square models, compared with PPFD (47.5-190), normal and tall models have higher frequencies of PPFD (9.5 47.5). The shallow atrium (WI = 1.0), however, sees an opposite trend. In round models, frequencies of PPFD (47.5-190) are significantly higher than those of PPFD (9.5-47.5). The frequency ranges for PPFD (47.5-190) and PPFD (9.5-47.5) are 45% - 24% and 22% - 25%, respectively. In addition, the big impact of WI or height on PPFD frequency can only be found in square models.

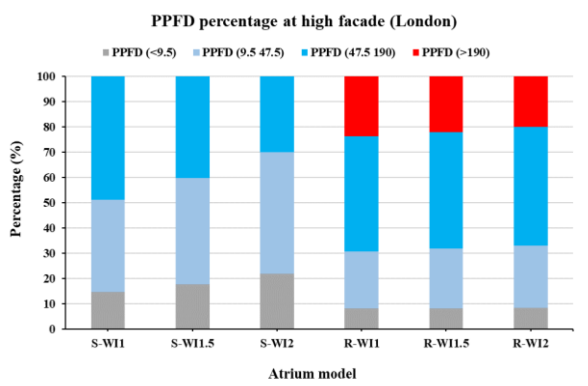


*Figure 9: Frequencies of PPFD ranges at high atrium facade levels in various atria (London).*

**3.5 Comparisons between different atrium positions**

Comparisons of frequencies of two PPFD ranges suitable for plants between different atrium positions are discussed in this section, including floor and three facade levels. Taking the high façade level as a reference, relative differences of frequencies of PPFD (9.5-47.5) or PPFD (47.5-190) [$R_{PPFD(9.5\ 47.5)}$ or $R_{PPFD(47.5\ 190)}$] can be expressed as follows:

$$R_{PPFD(9.5\ 47.5)} = [F_{PPFD(9.5\ 47.5),\ n} - F_{PPFD(9.5\ 47.5),\ high\ facade}] / F_{PPFD(9.5\ 47.5),\ high\ facade} \times 100\% \quad (2)$$

$$R_{PPFD(47.5\ 190)} = [F_{PPFD(47.5\ 190),\ n} - F_{PPFD(47.5\ 190),\ high\ facade}] / F_{PPFD(47.5\ 190),\ high\ facade} \times 100\% \quad (3)$$

where $F_{PPFD(9.5\ 47.5),\ n}$ or $F_{PPFD(47.5\ 190),\ n}$ is the frequency of PPFD (9.5-47.5) or PPFD (47.5-190) at floor, low or middle façade positions; $F_{PPFD(9.5\ 47.5),\ high\ facade}$ or $F_{PPFD(47.5\ 190),\ high\ facade}$ is the frequency of PPFD (9.5 47.5) or PPFD (47.5 190) at the high façade level; n means various atrium positions, including the centre floor, low and middle façades.

*Table 2: Relative differences of frequencies of PPFD (9.5-47.5) between high façade and other three positions (S1–3 mean models of S-WI1, S-WI1.5, S-WI2; R1-3 means models of R-WI1, R-WI1.5, R-WI2.).*

| | | $R_{PPFD\ (9.5\ 47.5)}$ (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | R1 | R2 | R3 |
| Beijing | Floor | 139 | 98 | 12 | 520 | 555 | 352 |
| | Low facade | 98 | 54 | -37 | 32 | 35 | 32 |
| | Middle facade | 66 | 58 | 28 | 16 | 22 | 26 |
| London | Floor | 68 | 45 | -16 | 175 | 160 | 71 |
| | Low facade | 42 | -1 | -49 | 12 | 10 | 10 |
| | Middle facade | 30 | 21 | -10 | 8 | 6 | 6 |

*Table 3: Relative differences of frequencies of PPFD (47.5-190) between high façade and other three positions (S1–3 mean models of S-WI1, S-WI1.5, S-WI2; R1-3 means models of R-WI1, R-WI1.5, R-WI2.).*

| | | $R_{PPFD\ (47.5\ 190)}$ (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | R1 | R2 | R3 |
| Beijing | Floor | -69 | -87 | -100 | -57 | -90 | -100 |
| | Low facade | -56 | -81 | -92 | 3 | 8 | 10 |
| | Middle facade | -33 | -51 | -74 | 3 | 3 | 4 |
| London | Floor | -58 | -100 | -100 | -57 | -100 | -100 |
| | Low facade | -68 | -91 | -96 | 6 | 8 | 6 |
| | Middle facade | -35 | -62 | -72 | 3 | 5 | 4 |

Tables 2 and 3 give the calculated values of $R_{PPFD(9.5\ 47.5)}$ and $R_{PPFD(47.5\ 190)}$, respectively. According to Table 1, compared with the high façade, the floor can receive much higher frequencies of PPFD (9.5-47.5) in most models at two locations, except for tall square atrium, while for the low façade significantly higher PPFD (9.5-47.5) frequencies can be just found in normal and shallow square atrium in Beijing and shallow square models in London. In addition, the middle façade level only sees higher PPFD (9.5-47.5) frequencies in Beijing's shallow square atrium. For the data of PPFD (47.5-190) in Table 3, the high façade in square models has higher frequencies than the other three positions at the two locations, whilst round models can only see this trend on the atrium floor. The middle and low facades levels in round models achieve very similar PPFD (47.5-190) frequencies as the high façade.

## 4. DISCUSSIONS AND CONCLUSION

Based on the simulation analysis of PAR availability and distributions in various atrium models at two locations, several key findings are discussed as follows.

Different from the daylighting metric applied for human visual function [9], the PAR metric (PPFD, µmoles/m$^2$/s) recommended in this study could be more useful in terms of planning greenery systems to enhance biophilic aspects of atrium. This metric adopted three PAR thresholds [10] instead of illuminance levels to evaluate if plants can have a normal growth in an atrium space. This could be used to provide quick solutions for supporting landscape design (interior) in a straightforward way.

The impact of atrium shape on PAR availability is significantly linked to the position in an atrium. At the atrium façade, it can be found that there are big differences of PAR availability between square and round atrium models. Generally, round atrium model could achieve higher PAR levels than square models, thus leading to a higher possibility to set vertical greenery systems at low or middle façade levels. On the other hand, at high façade levels, round models would be less suitable for vertical planting due to the excessively higher PAR levels. However, on the atrium centre floor, the impact of shape on PAR variation could be negligible, since a very similar level of PAR can be found for both square and round atrium models. This could be explained by the same volume and height applied for both atrium types.

In addition, geometric atrium properties (Well Index or height) could affect the PAR availability in an atrium. Similarly, the effect can be associated with the atrium shape and positions. At the atrium centre floor, increasing the WI or height would significantly lower the possibility to apply planting systems due to the deceasing frequency of proper PAR ranges. However, at the atrium façade, some different trends can be found. In square atrium models, an increasing WI or height could reduce frequencies of PAR falling in a proper range for sustaining plants growing, while the change of WI or height in round atrium models would not deliver big impact on such frequencies. Thus, round atrium models could provide designers with more opportunities for both spatial design and greenery system installations.

The frequency analysis indicates that climate conditions might not substantially influence the varying trends of PAR frequency according to the six atrium models studied here. Even though there is a big difference in climate between Beijing and London, the application of four frequency ranges (see section 2.3) might have reduced the divergence brought by the absolute PAR levels.

These results could contribute to design guidelines for the establishment of greenery systems in an atrium, and thus to increase opportunities to create a biophilic atrium with the 'green nature'.

Limitations and future work: this study only adopted two types of atrium. The atrium configurations were relatively simple. More work will be continuously conducted on parameters including interior properties, shapes, roofs, etc.

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